CALIFORNIA DIVISION OF MINES AND GEOLOGY
FAULT EVALUATION REPORT FER-188

PISGAH, BULLION, AND RELATED FAULTS
SAN BERNARDINO COUNTY, CALIFORNIA

by
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INTRODUCTION

The Pisgah and Bullion faults constitute a major zone of northwest-trending, right-lateral, Quaternary faults in the south-central Mojave Desert (Jennings, 1975). The zone extends about 110 km (65 miles) northwest from the vicinity of Twentynine Palms to Hector (Figure 1). Based on the work of others, Bortugno and Spittler (1986, sheet 5) have classified segments of both the Pisgah and Bullion faults as late Quaternary. Morton and others (1980) mapped "young-looking fault features" along the fault zone, which suggests faulting during the late Quaternary time (Figure 4). Mapping by Dibblee (1966; 1967a,b,c) and Dibblee and Bassett (1966) confirms that Pleistocene and possibly Holocene rock units are offset by the Pisgah, Bullion, and related faults.

Because the Pisgah and Bullion faults are recently active and because they lie within the current Mojave Desert study region, these faults are evaluated herein for possible zoning under the Alquist-Priolo Special Studies Zones Act (Hart, 1985). Only that part of the zone within and northwest of the Deadman Lake SE 7.5-minute quadrangle is evaluated here (Fig. 2). In addition, the Rodman, Bullion Mountain, and various unnamed faults in the study area also are evaluated (Fig. 2). The Mesquite Lake and West Bullion Mountains faults to the southeast were largely evaluated by Bryant (1986) and Hart (1987) and are not evaluated here.

SUMMARY OF AVAILABLE DATA

Although elements of the Pisgah and Bullion faults have been recognized for many years (e.g. Jenkins, 1938), these faults were first recognized in their entirety by Bassett and Kupfer (1963). Based on reconnaissance mapping (1:125,000 scale), they recognized the Bullion faults as an important right-lateral fault but did not recognize it as "Recent" (i.e. Holocene). They did recognize the Pisgah fault as "Recent", though, because it offsets young flows of the Pisgah and Sunshine Crater. Because Bassett and Kupfer's base map is of poor quality and most of their mapping was reconnaissance, their faults are not addressed further where better data is available.

Later mapping by Dibblee (1966; 1967a,b,c) and Dibblee and Bassett (1966) dipicted the Pisgah and Bullion faults in greater detail (1:62,500) as well as some unnamed faults, and remains as the most comprehensive work available today. They clearly show the Pisgah and Bullion faults to be important right-lateral faults (Fig. 3).

Later reconnaissance work by Bull (1978) classified these and other faults of the Mojave Desert in terms of activity, using linearity of mountain fronts and other tectonic geomorphic interpretations. Morton and others (1980) provide the first detailed maps (1:24,000 and 1:62,500 scales) of recently active faults based on aerial photographic interpretations of geomorphic features. Their maps provide a useful source of data for this fault evaluation study.

Regional analyses of Garfunkel (1974) and Dokka (1983) provide estimates on the magnitude and timing of faulting. Garfunkel proposed 20 to 40 km of slip for the Pisgah fault during late Cenozoic time. Dokka estimated only 6.4 to 14.4 km of combined right-slip for the Pisgah and newly named Rodman fault during the last 20,000,000 years. Wesnousky (1983) summarized the work of others in his assessment of Quaternary faults, slip rates, and seismic hazards. He introduced the name "Bullion Mountain" to a zone of faults in the southeastern part of the study area
(Fig. 3).

These faults--the Pisgah, Bullion, Rodman, Bullion Mountains, and several unnamed faults are discussed individually below.

Pisgah Fault

This fault is mapped by Dibblee and Bassett (1966) and Dibblee (1966) as a well-defined, 35-km-long, right-lateral fault (Fig. 3). It is shown both to offset and be concealed by Holocene and/or latest Pleistocene alluvium (Qa) and basalt lava (Qb). It offsets all Pleistocene lava of Sunshine Crater (Qbs) and older units. The amount of offset is not readily determined from the maps of Dibblee and Dibblee and Bassett, although the northerly and southerly margins of Qbs appear to be offset right-laterally about 0.7 km and 0.5 km at X-X' and Y-Y', respectively, in the Lavic quadrangle (Fig. 3). The Pisgah fault is shown to be concealed and inferred north of Highway I-40 (old U.S. 66). To the south, the fault steps right and presumably connects in the subsurface with the Bullion fault.

Bull (1978, Fig. 18), using geomorphic evidence, classified a portion of the Pisgah fault as an active, strike-slip fault (see Fig. 3). Based on limited field and aerial photo observations in the Sunshine lava flows (Qbs of Dibblee, 1966), Bull was able to draw several conclusions that bear on the magnitude and recency of slip along the Pisgah fault. First, he (p. 111-112) estimated the age of the Sunshine flows to be late Pleistocene, based on the comparative preservation of flow features (in sec. 30, T.7N., R.6E.) to nearby dated flows. Second, Bull (p. 111) noted lineaments of angular blocks of basalt in the same area and that some of the faces of the blocks was unvarnished and unweathered. He tentatively concluded that the "fault-stirred" blocks was "suggestive of fault rupture during the last 3,000 years, and perhaps of several movements during the Holocene" (this may be the same as my locality 4, Fig. 4). Finally, Bull (p. 116-118) noted a streaming- out of basaltic cobbles (colluvium) along the Pisgah fault in sec. 13, T.7N., R.6E. (near X-X' in Fig. 3). He recognized more than a kilometer of strike-slip displacement from a point-source uphill (east?) of the fault, but is not specific as to the precise location or age of the cobble source (Dibblee, 1966, shows both Pleistocene and mid-Cenozoic basalt in this area).

Morton and others (1980) mapped "young-looking" traces of the Pisgah fault over a distance of 25 km in the Cady Mts. 15' and Sunshine Peak 7.5' quadrangles (Fig. 4). They did not recognize youthful features along the northern and southern segments of the fault. Their work was based solely on the interpretation of low-sun angle aerial photographs taken January 1975. [These photos could not be located for our study.] Their work was not field-checked. As shown on Fig. 4, Morton and others mapped the Pisgah fault as a relatively well-defined and continuous feature. Their evidence for recency include linear scarps, trenches, and ridges, some of which are developed in young alluvium (locality 3, Fig. 4) and Pisgah lava flows (locality 1, Fig. 4). Dibblee and Bassett (1966) considered the Pisgah basalt flows to be very late Pleistocene or Holocene in age. Bassett and Kupfer (1963, p. 39) also noted that the lava surface at Highway I-40 (locality 1) was offset about six feet (west side down). Dokka and Glazner (1982, p. 29) believe that "significant movement" occurred along this segment of the fault in the last 10,000 to 20,000 years.

Data presented by Dyer and others (1963, App. A and Fig. 2) suggests that the Pisgah fault may be a groundwater barrier in the vicinity of Highway I-40. Wells located west of the fault show the groundwater elevation to be about 1780 to 1790 feet. One of these wells is located in Fig. 5 (Well R1 in sec. 19). Two other wells 7 and 5 km to the north and northeast (E1 and M1) show the groundwater levels to be 76 and 91 feet lower, respectively. A possible groundwater barrier may exist just below the surface of the young alluvium where vegetation and tonal features were identified by Morton and others (see Fig. 4) and this writer (see Fig. 5).

<u>Bullion Fault</u>

Dibblee (1966, 1967a, 1967b) provides the most comprehensive geologic map along the Bullion fault. As shown by him, the fault is a rather complex zone of surface and concealed faults that extends southeastward from Sunshine Crater (Fig. 3). The northern segment has an overlapping, right-step relation with the Pisgah fault, the two faults constituting a single zone of mainly right-lateral faults. The individual strands of the Bullion fault occupy a zone as much as 3 km wide. According to Dibblee, Holocene and/or late Pleistocene alluvium (Qa) is offset against Pleistocene and older deposits in several places along a 26 km segment of the fault (H? on Fig. 3). The north and south segments of the fault are shown to be concealed by all Pleistocene and Holocene deposits, and apparently are inactive or at least poorly defined.

Bassett and Kupfer (1963) show the Bullion fault to extend northwest to a point about a mile west of Sunshine Peak. The fault does not offset any unit younger than Pleistocene. Only the northwest end of fault is plotted on Fig. 3.

In his geomorphic assessment of range-front faults, Bull (1978) classified the north-central segment of the Bullion fault as an active strike-slip fault, and all other segments as inactive. He provided no additional data on the fault.

Morton and others (1980) mapped "young-looking fault features" along the Bullion fault (they referred to it as the Pisgah fault) over a distance of 42 km (Fig. 4). Their work was limited to the interpretation of aerial photographs; no field work was done. Although no conclusions are made regarding the age of faulting, they imply that some of the traces are late Pleistocene or Holocene based on their descriptions of "youthful scarps" or scarps in alluvium (localities 5, 6, and 10, Fig. 4) and "hillside trench" (localities 7 and 8). The identification of right-laterally deflected drainages (e.g. locality 10) and alternately facing scarps indicate dominant right-slip. My assessment of their features are annotated in green on Fig. 4. Much of their data, however, are more permissive than mandatory for Holocene faulting and some of the features are the result of differential erosion across contrasting lithologic units.

The only other works pertinent to understanding the nature of the Bullion fault are those of Moyle (1984) and Akers (1986). Based largely on gravity anomalies, they show that the Bullion fault zone coincides with a steep, buried escarpment along the southwest flank of the Bullion Mountains. The escarpment in turn constitutes the northeast margin of a deep, elongate basin of deposition. This basin is calculated to be more than 3,000 m deep between Gypsum Ridge and Deadman Lake. The fact that the basin lies in the right-stepover between the Bullion and Mesquite Lake faults implies that the two faults are structurally related. If so, a large amount of strike-slip displacement -- possibly 10 km or more -- probably occurred along these faults. This is consistent with maximum displacements estimated for the Pisgah fault to the northwest (see above).

Rodman Fault

This fault was initially mapped by Dibblee (1966) as an unnamed fault that lies 6 km west of the Pisgah fault (Fig. 3). The fault extends a kilometer or so to the northwest of Figure 3 into the Rodman Mountain quadrangle (Dibblee, 1964). The fault apparently was named by Dokka (1983) in his assessment of the magnitudes of offset of faults in the Mojave Desert. Dibblee shows the fault to be a projection of, but not to connect with, the Bullion fault to the southeast. He mapped the fault as offsetting Pleistocene units. Elsewhere, it is shown to be concealed by Holocene and/or late Pleistocene alluvium (Qa) and, locally, by older Pleistocene alluvium (Qoa). A southeastern extension of the Rodman fault was mapped as an unnamed fault by Bassett and Kupfer (1963), who show it to offset late Cenozoic units (Fig. 3). They do not show the fault to offset alluvium. Morton and others (1980) do not evaluate the Rodman fault. Bull (1978) considered the fault to be an inactive, strike-slip fault, based on geomorphic expression (Fig. 3).

Bullion Mountain Fault zone

This zone of left-stepping faults was mapped (unnamed) by Bassett and Kupfer (1963) and Dibblee (1967a, 1967c). The name was first(?) applied by Wesnousky (1986), who based his work on Jennings (1975; compiled from Dibblee), as part of his assessment of earthquake risks. Dibblee, whose mapping is the most detailed and complete, shows two of the faults depicted on Figure 3 both to offset and be concealed by Holocene and/or late Pleistocene deposits and Pleistocene deposits. He shows a central strand to be a right-lateral fault, but all of his cross-sections show down-to-the-west components of offset (as much as 500 m) on vertical faults. Although the left-stepping zone apparently extends to the southeast (Fig. 1), it is not evaluated beyond the Deadman Lake quadrangle.

Bull (1978) considered the northwest strands to be inactive and one of the southwest strands to be slightly active.

Unnamed Faults

Dibblee and Bassett (1966) mapped two other faults to the east of the Pisgah fault -- identified as A and B on Figure 3 -- which are considered in this study. Fault A is inferred to offset older Pleistocene deposits and is concealed by younger deposits. Fault B is entirely concealed. Bull (1978) considered both faults to be inactive. Another fault, identified as fault C on Figure 5, was not previously mapped.

SEISMICITY

Seismicity in the vicinity of the Pisgah and Bullion faults is shown on Figure 6, which depicts only well-located earthquakes (A and B quality). Epicenters are for the 1932 to mid-1985 period, based on data from the California Institute of Technology (1985). Most of the epicenters are for the last 15 years when the seismic network was expanded.

Except for the M 5.2 earthquakes of 9/25/65 (Real and others, 1978) all of the earthquakes near the faults studied are less than M 4. The M5.2 earthquake and four smaller events lie close to and may be associated with the Rodman fault.

Three clusters of epicenters lie just east of and presumably are associated with the Pisgah fault and fault B. Other epicenters scattered along the Pisgah, Bullion, Rodman, and B faults suggest that these faults may be seismically active. Although some of the seismicity may be related to mining at or west of the Pisgah Crater, the events are too widely scattered and probably too large (some are M 3.0-3.9) to be man-caused. In addition, some of the events south and east of the Pisgah Crater lie within the Marine Corps Training Center where numerous explosions (bombs, artillery) occur. Again, the M 3.0-3.9 events appear to be too large to be caused by explosives, although the smaller ones could have such a cause.

Little seismicity is associated with the Bullion Mountain fault or the southeast end of the Bullion fault. Neither of these segments are mapped as active.

INTERPRETATION OF AERIAL PHOTOGRAPHS AND FIELD CHECKING

All of the faults evaluated in this study were carefully interpreted on aerial photographs for geomorphic and other features suggestive of recent faulting. Most useful were the 1:24,000-scale photos of the U.S. Department of Agriculture (1952 and 1953). U.S. Bureau of Land Management (1977, 1978) photos also were used, but were less satisfactory because of their 1:30,000 scale.

Field checking was done for selected segments of the Pisgah and Bullion faults. This work was conducted on January 27-30, 1987, with the assistance of Ed Bortugno of DMG. Roger Twitchell, Natural Resources Manager at the Marine Corps Training Base, arranged access to the Marine base on January 28 and 29.

The results of the photo interpretations and field observations are summarized on Figures 4 and 5. An attempt was made to verify the fault traces and annotations of Morton and others (1980), although additional interpretations were added by this writer (this information is shown in green on Fig. 4). Additional fault data are plotted on the Hector 7.5' quadrangle (Fig. 5), which was not available when Morton and others published their results. General annotations for other faults appear on Figure 3 where detailed mapping was considered to be unnecessary.

This writer's observations are summarized as follows:

Pisgah Fault

This fault is very well-defined over most of its length by relatively narrow zones of linear scarps and ridges, sidehill benches, truncated spurs, closed depressions, and other features in late Pleistocene and Holocene alluvium and basalt lava flows in the Sunshine Peak and Hector 7.5' quadrangles (e.g. localities 1, 2, 3, 4, 14, and 15 in Figures 4 and 5). Right-laterally offset drainages and ridges clearly identify the fault as a steeply-dipping right-lateral fault. Right-lateral slip also is indicated by the presence of left-stepping faults that partly diverge from the main trace near locality 4 in sections 19, 30, 31, and 32. Evidence for recency of activity includes:

1. Scarps and linear ridges in the Pisgah lava (e.g. localities 1 and 16, Fig. 5; Photos 1 and 2), which is essentially unweathered and presumably of Holocene or latest Pleistocene age.

2. A sidehill bench in fault-stirred rubble of late(?) Pleistocene basalt at locality 4 (Fig. 4; also Photo 3) strongly suggests Holocene activity. Where examined in the field, the rubble below the sidehill bench had faces that ranged from strongly weathered to unweathered and unvarnished. Bull (1978, p. 111) made similar observations (discussed in preceding section) and concluded that displacement occurred on the Pisgah fault in the last 3,000 years. In the same area, several large clasts were observed resting on young sediment of a closed depression as much as 8 to 10 m from the scarp. Because the rubble is well-interlocked on the scarp, it is assumed that the blocks were dislocated as a result of one or more large earthquakes during Holocene time.

3. Scarps and tonal feature are present in alluvium of probable Holocene age (e.g. at locality 3, Fig. 4).

The Pisgah fault becomes progressively less active and less well-defined north of the Pisgah lavas and cannot be identified north of section 31 (Fig. 5). To the south, the fault is difficult to map in the young alluvium, although very weak evidence suggests that it connects complexly with the Bullion fault in the Galway Lake and Lavic SE quadrangles (Fig. 4). The most easterly fault strand, identified by a broad, eroded scarp and monoclinal fold or anticline at locality 17, appears to offset late Pleistocene basalt of the Sunshine flow (Qbs) right-laterally, but evidence of Holocene activity is weak or absent.

Although the well-developed features in the late Quaternary deposits indicate that a substantial amount of right-slip has occurred during that period, the apparent offsets of Qbs at X-X' and Y-Y' on Figure 3 suggest about 700 and 500 m of right-slip, respectively. These offsets can be verified on aerial photos (e.g. see locality 17, Fig. 4). If the unit is assumed to be 500,000 years old, then slip-rates of 1.4 and 1.0 mm/yr are calculated. However, the Qbs lava may have been deposited on an uneven surface and no matching piercing points can be seen on the aerial photos. Nonetheless, dark colluvium (basalt?) of probable latest Quaternary age appears to be offset about 160 m on photos AXL-10K-153 and 154 (locality 15), which appears to be consistent with the calculated slip rates. This locality was not examined in the field. An apparent offset of the north edge of the Pisgah lava at locality 2 (Fig. 5) is about 15 m along the projected trace of the fault (fault is concealed by rubble in the field). Assuming the lava is 10,000 years old (it is unweathered and only weakly varnished), then a slip rate of 1.5 mm/year can be calculated. A vertical component of slip is better constrained at locality 1 (Fig. 5) where the young lava surface is offset (down to the west) about 2 m. This would give a vertical component of slip of 0.2 mm/year for a 10,000 year old surface.

Bullion Fault

Based on the interpretation of geomorphic features observed on aerial photographs, the Bullion fault consists of a more or less continuous zone of recently active faults that extends southeastward from the west edge of the Lavic SE quadrangle to section 25 of the Deadman Lake NW quadrangle (Fig. 4). The location of the fault is largely concealed by Holocene alluvium and dune deposits to the southeast of Section 25, but weak evidence (e.g. locality 13) suggests that it may connect as a right-step with the Mesquite Lake fault across the Deadman Lake depression. The latter feature is the surface expression of a large, 3 km-deep basin that extends from Deadman Lake to Gypsum Ridge (Moyle, 1984). To the northwest, the Bullion fault appears to have a right-step relation with the Pisgah fault previously described, although the surface connection is subtle and largely concealed by Holocene alluvium.

The well-defined strands of the Bullion fault zone are identified by the usual linear scarps, troughs and sidehill benches, right-laterally deflected drainages, shutter ridges, and other features indicative of late Quaternary right-lateral displacement (e.g. localities 6, 7, 8, 9, 10, 11, 12 of Fig. 4; photo 4). Some of these features are ephemeral, and suggestive of Holocene slip.

The only locality examined in the field was locality 12 in the Deadman Lake NW quadrangle. Here, the fault is exposed as an 8 to 10 m wide zone of sheared and brecciated older (Pleistocene?) gravels in the north wall of main drainage channel that is offset right-laterally about 10 m. To the north is a narrow sidehill bench along which every drainage is offset for a distance of 200 to 300 m. Three or four of these drainages are very minor (young) debris flow channels half a meter deep or less. Each of these drainages is right-laterally offset an estimated 1 to 2 m, suggesting one or two fault rupture events in (late?) Holocene time. Larger drainages are offset by greater amounts, clearly demonstrating repeated displacements in the same sense. To the south of the main channel is another sidehill bench that aligns with offset drainages and assymmetric alluvial cones that are clearly Holocene (no desert varnish on clasts). Other strands of the fault appear almost as well-defined and youthful to the northwest (e.g. localities 6, 8 and 10).

Recent displacement appears to be distributed along two or three strands in several places (e.g. northwest of locality 6 and near localities 7, 9, and

10), comprising a zone as much as a kilometer wide. The southeastern segment, shown by Dibblee northeast of Bullion Wash (Fig. 3), cannot be verified as recently active or even located, although it is largely covered by young alluvium and dunes.

Slip-rates have not been determined for the Bullion fault, although the geomorphic evidence suggests a late Quaternary rate comparable to the Pisgah fault (i.e. 1-1.5 mm/yr).

Rodman fault

Discontinuous geomorphic evidence indicates that the Rodman fault is a linear, right-lateral, strike-slip fault of late Quaternary age. This applies both to the northwest segment mapped by Dibblee (1966) and to the southeast segment mapped by Bassett and Kupfer (1963) (see Fig. 3). The evidence includes linear scarps and tonal features in Pleistocene alluvium and basalt of Lava Mts. (QTb). Features are better developed and more continuous in the southeast segment and some of the larger drainages are deflected right-laterally. However, most of the scarps are degraded, smaller drainages do not appear to be deflected, and nowhere does the fault offset Holocene alluvium. In fact, well developed features are not observed locally in older alluvium (Qoa). Although the fault was clearly active in Pleistocene time, it apparently became inactive in latest Pleistocene time. The fault was not field-checked.

Bullion Mountain Fault

Evidence for the location of this left-stepping zone of faults (Fig. 3) consists of rather well-defined linear troughs, scarps, and tonals in bedrock. The features appear to be due to differences in erosion rates at lithologic contrasts (i.e. fault-line features). The several fault strands do not systematically offset drainages and ridges. More faults can be observed on aerial photographs than are shown by Dibblee (1967a and 1967c) and the several strands shown on Figure 3 probably interconnect to some degree.

Other Faults

Fault A of Dibblee and Bassett (1966) (see Fig. 3) was not verified on aerial photographs. However, a minor fault --fault C-- a few hundred meters to the east could be mapped as a weak zone of discontinuous broad scarps, tonals, and possibly deflected drainages in older fan deposits (Fig. 5). Fault C is only partly defined and appears to lack geomorphic evidence of Holocene activity.

Fault B to the east (Fig. 5) is somewhat better defined by broad scarps, tonal lineaments, a sidehill bench, and deflected drainages. The two overlapping strands bound a broad closed depression, indicating extension and probable right-lateral displacement. A linear scarp in basalt lava of the Pisgah Crater, which is early Holocene or latest Pleistocene in age, suggests probable Holocene offset (down to the east) at the south end of the fault. The south strand of fault B was walked-out for 0.6 km at locality 18 where a highly degraded scarp and two deflected drainages were observed. However, no fault exposures were seen.

CONCLUSIONS

The Pisgah and Bullion faults constitute an important zone of faults that is about 80 km (50 miles) long in the study area. Associated with this zone are the Rodman fault to the west and the Bullion Mountain fault and faults A, B, and C to the east (Fig. 1 and 2).

Pisgah Fault

The Pisgah fault is the most prominent element in the northwest part of the zone. The fault is a well-defined structural and geomorphic feature that has had significant right-lateral displacement. Dokka (1983) estimates 6.4 to 14.4 km of combined right-slip for the Pisgah and Rodman faults in late Cenozoic time. Bull (1978) implies that more than a kilometer of right-slip in late(?) Quaternary time. This writer infers as much as 0.7 km of offset of the basalt lava of the Sunshine flows (considered to be late Quaternary in age by Bull) and about 15 m of right-lateral offset of the basalt lava of the Pisgah flows (which Dibblee, 1966, considers to be very late Pleistocene or Holocene in age). Although matching piercing points and/or reliable ages of units are lacking, it would appear that the Pisgah fault has had a 1 to 1.5 mm rate of slip during late Quaternary time. Southwest- and northeast-facing scarps also indicate smaller components of vertical displacement locally.

Geomorphic features consistent with the inferred slip-rates are well developed in late Quaternary volcanic and alluvial deposits. These features include linear scarps and ridges, sidehill benches, closed depressions, and right-laterally deflected drainages. Evidence of Holocene activity includes linear scarps and ridges in the Pisgah flows, which are latest Pleistocene to Holocene in age. Weak scarps and tonal features in young (Holocene?) alluvium also indicate Holocene activity, although the fault is partly concealed by Holocene alluvium. Bull (1978) believed that the fault-stirred blocks in the Sunshine flows suggested faulting as recently as 3,000 years ago. Seismicity near the Pisgah fault suggests that the fault is historically active at depth.

The Pisgah fault is a well-defined surface feature from section 6 in the Hector quadrangle (Fig. 5) to the southern part of the Sunshine Peak quadrangle (Fig. 4). The right-step connection between the Pisgah fault and the Bullion fault to the south is largely concealed by Holocene alluvium and probably is complex.

Bullion Fault

This fault is a southeastward continuation of the Pisgah fault, but it is more complex and locally not as well-defined. Well-defined strands extend southeastward from sec. 29 in the Lavic SE quadrangle to sec. 25 of the Deadman NW quadrangle (Fig. 4). The intervening strands are defined by linear scarps, sidehill benches and trenches, right-laterally deflected drainages, and shutter ridges. Although matching piercing points were not identified across the fault, the magnitude of the shutter ridges (partly breached) suggest at least a kilometer of right-lateral offset in Quaternary time. Small offsets (1 to 2 m) of several minor debris flow channels north of locality 12 (Fig. 4) suggest that faulting may have occurred in late Holocene time and that the maximum displacement was no more than 1-2 m per event. The preservation of small-scale, ephemeral features (e.g. sidehill benches and deflected drainages) certainly indicates Holocene activity. Moreover, the larger drainages generally are offset more than smaller drainages, indicating repeated, systematic faulting in late Quaternary time. As a whole, the best geomorphic features of the Bullion fault are about as well developed as the features associated with the Pisgah fault, suggesting that both faults have had comparable displacement and slip-rates in late Quaternary time.

The Bullion fault cannot be followed as a continuous surface feature to the northwest or southeast of the well-defined segment just described. Dibblee (Fig. 3) shows these segments to be concealed by Holocene and/or late Pleistocene alluvium. Only weak, discontinuous features exist hinting at the possible surface locations of these distal projections (Fig. 4). It is believed that the activity on the Bullion fault steps right in either direction to connect complexly with the Pisgah and Mesquite Lake faults, respectively. If so, then extensional basins should exist in the step-over areas. No such depression is evident in the Pisgah-Bullion step-over, although the area may be receiving alluvial fan sedimentation at a rate exceeding the inferred downwarping. To the southeast, there is evidence of a deep sedimentary basin (Moyle, 1984) between the concealed traces of the Bullion and Mesquite Lake faults which centers between Deadman Lake and Gypsum Ridge (Fig. 3). Apparently, Deadman Lake is the active remnant of this subsiding basin.

Rodman Fault

The Rodman fault is a 23 km-long fault that is discontinuously exposed in Pleistocene and older deposits (Fig. 3). Although defined by erosional, fault-line features locally (scarps, linear drainages), there is little geomorphic evidence to sugggest that it has been active in latest Quaternary time. In fact, the fault is concealed by Holocene and late Pleistocene units. However, several earthquakes (Fig. 6) suggest it may be active at depth. The linearity of the fault and apparent drag of stratified units adjacent to it, suggest that the fault has had significant right-slip displacement. Its geometry suggests that the fault is a northwestern projection of the Bullion fault zone, from which it is separated by a syncline.

Bullion Mountain Fault Zone

This is a loosely-defined zone of left-stepping faults that lies several kilometers east of and parallel to the Bullion fault. Based on the geometry and on Dibblee (1966, 1967a, 1967c), the zone consists of discontinuous vertical faults with dominant right-slip and components of dip-slip (mostly down to the southwest). The faults offset pre-Quaternary rocks and may offset Pleistocene alluvium locally. However, they are largely concealed by late Quaternary units and lack geomorphic evidence of recent activity.

Other Faults

Dibblee and Bassett (1966) infer two faults east of the Pisgah fault--designated here as faults A and B (Fig. 3). Fault A is inferred to offset older Pleistocene fan deposits, but was not verified as a recently active feature on aerial photographs. However, fault C a few hundred meters to the east can be mapped in the older fan deposits as a weak zone of degraded or erosional features (Fig. 5). This minor fault lacks evidence of Holocene activity, but probably was active in late Pleistocene time as a right-lateral fault.

Fault B, which Dibblee and Bassett show to be concealed, can be mapped as a moderately well-defined zone of subtle scarps, sidehill bench, linear drainages and tonal features, along which several drainages appear to be deflected right-laterally. A linear scarp in basalt lava of the Pisgah flows (latest Pleistocene or Holocene age) indicate that the fault may be Holocene-active. Nearby seismicity suggests that the fault may be active at depth.

RECOMMENDATIONS

Based on the evaluations made, the following faults are considered to be Holocene active and sufficiently well-defined to warrant zoning under the Alquist-Priolo Act (Hart, 1985). Those fault strands recommended for zoning are highlighted in yellow on Figures 4 and 5.

Pisgah fault--this fault has good evidence of Holocene activity and is well-defined between sec. 6 in the Hector quadrangle southeastward through the Sunshine Peak quadrangle to the southwest corner of the Lavic Lake quadrangle. The southeastern segment in the Lavic SE quadrangle probably should be zoned as it is moderately well-defined and may be Holocene active.

Bullion Fault--this fault has abundant evidence of Holocene activity and is moderately-to well-defined from the western margin of the Lavic SE quadrangle southeastward through the Hidalgo quadrangle to sec. 25 of the Deadman Lake NW quadrangle. Although only discontinuously defined to the southeast, the aligned strands in secs. 30, 31, and 32 also probably should be zoned.

Fault B--this fault is moderately well-defined where mapped on the Hector quadrangle.

The references cited on each of the Special Studies Zones maps should be Hart (1987, this FER) and Morton and others (1980). Dibblee and Bassett (1966) and Dibblee (1966, 1967a, 1967b) may be cited as substantially confirming sources, although none of their traces are recommended for use on the SSZ maps.

Other faults evaluated that are not recommended for zoning are as follows:

Bullion fault--the largely concealed northwest and southeast segments shown on Fig. 3 are either not defined or poorly defined as surface features.

Rodman fault--this fault lacks evidence of Holocene activity and is only discontinuously defined as a surface trace.

Bullion Mountain fault zone--none of these strands appear to be active and only locally are they well-defined in older rocks.

Other faults--faults A and C are not defined or poorly defined as surface features and lack evidence of Holocene activity.

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REFERENCES CITED

Akers, J.P., 1986, Geohydrology and potential for artificial recharge in the western part of the U.S. Marine Corps Base, Twentynine Palms, California, 1982-83: U.S. Geological Survey Water-Resources Investigations Report 84-4119, 18 p., 2 plates (1:62,500 scale).

Bassett, A.M., and Kupfer, D.H., 1963, a geologic reconnaissance in the southeastern Mojave Desert, California: California Division of Mines and Geology Special Report 83, 43 p., 1 pl., scale 1:125,000. (Same map as U.S. Geological Survey MF-205 by Kupfer and Bassett, 1962.)

Bortugno, E.J., and Spittler, T.E., 1986, Geologic map of the San Bernardino quadrangle, California: California Division of Mines and Geology Regional Geologic Map Series, Map No. 3A, 5 sheets (Recency of faulting, Sheet 5), scale 1:250,000.

Bryant, W.A., 1986, Pinto Mountain, Mesquite Lake, Copper Mountain, and related faults, southern San Bernardino County, California: California Division of Mines and Geology Fault Evaluation Report FER-181 (unpublished file report).

Bull, W.B., 1978, Tectonic geomorphology of the Mojave Desert, California: U.S. Geological Survey Technical Report 14-08-0001-G-0394, 188 p.

California Institute of Technology, 1985, Magnetic tape catalog, southern California earthquakes for the period 1932 to 1985: Seismological Laboratory, California Institute of Technology (unpublished).

Dibblee, T.W., Jr., 1964, Geologic map of the Rodman Mountains quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-430, scale 1:62,500.

Dibblee, T.W. Jr., 1966, Geologic map of the Lavic quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-472, scale 1:62,500.

Dibblee, T.W., Jr., 1967a, Geologic map of the Deadman Lake quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-488, scale 1:62,500.

Dibblee, T.W., Jr., 1967b, Geologic map of the Emerson Lake quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-490, scale 1:62,500.

Dibblee, T.W., Jr., 1967c, Geologic map of the Ludlow quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-477, scale 1:62,500.

Dibblee, T.W., Jr., and Bassett, A.M., 1966, Geologic map of the Cady Mountains quadrangle, San Bernardino County, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-467, scale 1:62,500.

Dokka, R.K., 1983, Displacements on late Cenozoic strike-slip faults of the central Mojave Desert, California: Geology, v. 11, n. 5, p. 305-308.

Dokka, R.K., and Glasner, A.F., 1982, Late Cenozoic tectonic and magmatic evolution of the central Mojave Desert in Geologic Excursions in the California desert: Geological Society of America, Cordilleran Section Guidebook, p. 1-29.

Dyer, H.B., Bader, J.S., Giessner, F.W., and others, 1963, Wells and springs in the lower Mojave Valley area, San Bernardino County, California: California Department of Water Resources Bulletin No. 91-10, 19 p, 4 app., 1 plate (1:62,500 scale).

Garfunkel, Z., 1974, Model for the late Cenozoic tectonic history of the Mojave Desert, California, and its relation to adjacent regions: Geological Society of America Bulletin, v. 85, p. 1931-1944.

Hart, E.W., 1985, Fault-rupture hazard zones in California: California Division of Mines and Geology Special Publication 42 (revised), 24 p.

Hart, E.W., 1987, Northwest extension of Mesquite Lake fault, San Bernardino quadrangle, California: California Division of Mines and Geology Fault Evaluation Report FER-181, Supplement No. 1 (unpublished file report).

Jenkins, O.P. 1938, Geologic map of California: California Division of Mines and Geology, scale 1:500,000.

Jennings, C.W., 1975, Fault map of California, with locations of volcanoes, thermal springs, and thermal wells: California Division of Mines and Geology Geologic Data Map Number 1, scale 1:750,000.

Morton, D.M., Miller, F.K., and Smith, C.C., 1980, Photo-reconnaissance maps showing young-looking fault features in the southern Mojave Desert, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1051, sheets 1-7, scales 1:24,000 and 1:62,500.

Moyle, W.R., Jr., 1984, Bouguer gravity anomaly map of the Twentynine Palms Marine Corps Base and vicinity, California, showing thickness of sedimentary deposits, deep wells and geology: U.S. Geological Survey Water-Resources Investigation Report 84-4005, scale 1:62,500.

Real, C.R., Toppozada, T.R., and Parke, D.L., 1978, Earthquake epicenter map of California (showing events from 1900 through 1974): California Division of Mines and Geology Map Sheet 39, scale 1:1,000,000.

U.S. Bureau of Land Management, 1977, Aerial photographs CA93-77 10-22 to-25, 11-22 to-24, black and white, vertical, scale 1:30,000.

U.S. Bureau of Land Management, 1978, Aerial photographs CAHD-77 9-40, 19 to 21; 9-41, 17 to 21; 9-42, 16 to 20; 9-46, 8 to 10; 9-47, 6 to 10; black and white, vertical, scale 1:30,000.

U.S. Department of Agriculture, 1952 and 1953, Aerial photographs AXL 5K-51 to 62 and 109 to 122, 6K-161 to 175, 7K-146 to 157, 8K-33 to 44, 9K-79 to 96; 10K-53 to 58 and 145 to 163; 11K-121 to 126; 12K-42 to 44, 32K-116 to 129 and 161 to 176, 37K-162 to 173, 38K-2 to 10 and 83 to 92, black and white, vertical, scale 1:24,000.

Wesnousky, S.G., 1986, Earthquakes, Quaternary faults, and seismic hazard in California: Journal of Geophysical Research, v. 91, n. B12, p. 12587-12631.

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Photo 1. View to north of linear ridges and low scarp along Pisgah fault in unweathered basalt lava of Pisgah flows (Locality 1, Fig. 5). Linear ridges consist of broken lava and rubble, presumably formed by strike-slip displacement of thin lava flow. Surface at left is about 2 m lower than surface behind ridges.

Photo 2. Same location as Photo 1, but looking toward southeast at scarp and ridges in basalt of Pisgah flows. Lava is considered to be latest Pleistocene or Holocene in age.

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Photo 3. Looking north along scarp of Pisgah fault in basalt of Sunshine lava flows of probable late Pleistocene age (Locality 4, Fig. 4). Sidehill bench (not shown) lies just above portion of scarp shown. Faces of fault-stirred rubble range from weathered and stained to relatively fresh, indicating repeated adjustment of rubble. Rubble clast to left, which is resting on young sand of closed depression, appears to have been shaken from rubble slope, presumably by late(?) Holocene earthquake.

Photo 4. Sidehill bench (arrows) formed by recent movement of Bullion fault on steep slope in Pleistocene gravel deposit just north of locality 13 (Fig. 4). If fault were inactive, bench would have been overwhelmed with debris. All drainages that cross bench are offset in right-lateral sense. Several minor drainages (debris flow channels) show 1 to 2 m of offset; larger drainages have greater offsets.

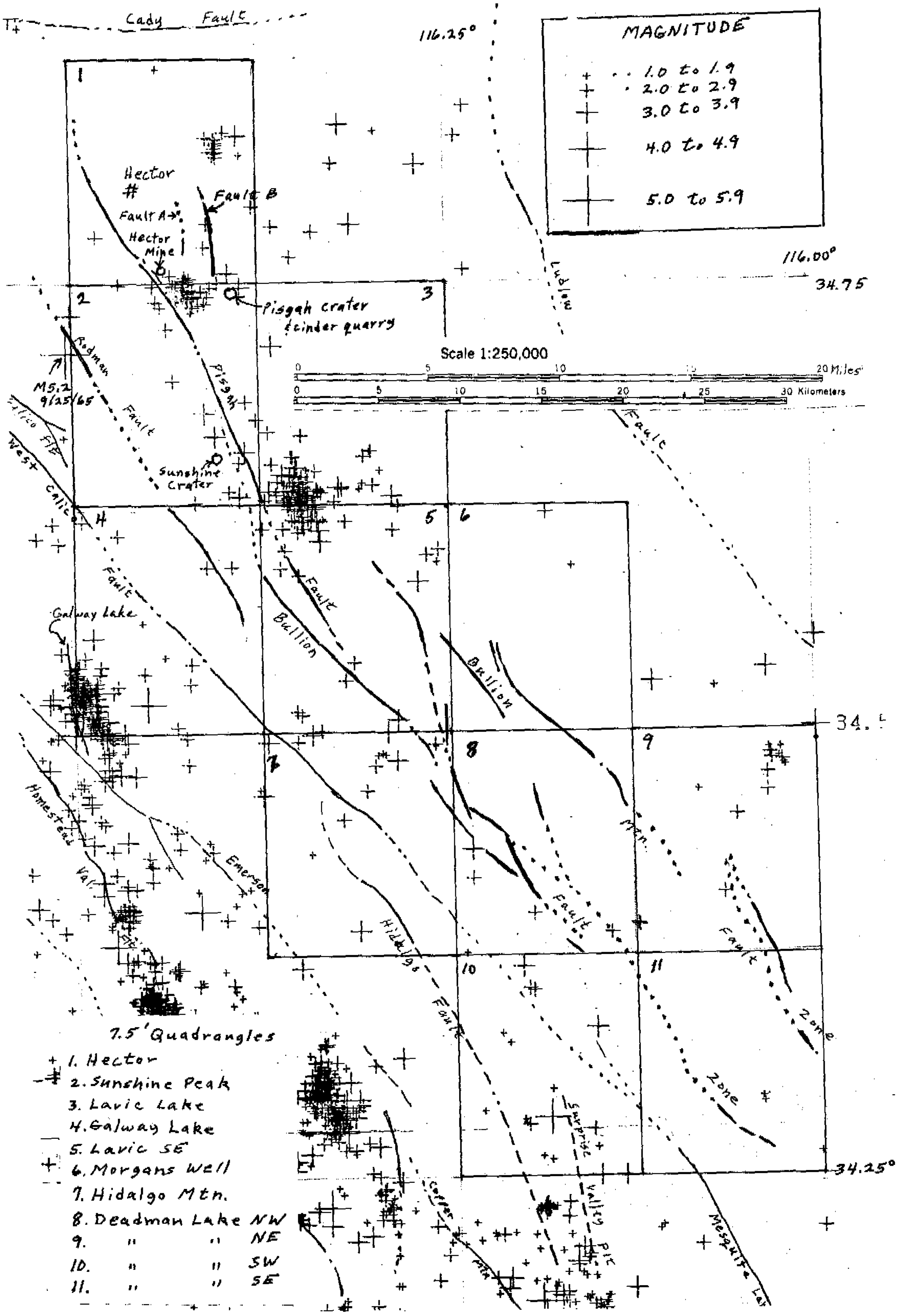

Figure 6 (to FER-188). Seismicity (A and B quality) in the vicinity of the Pisgah and Bullion faults for the period 1932 to mid-1985, based on data obtained from the California Institute of Technology (1985) and Real and others (1978).